

Charged Higgs Boson Effects in the Production and Decay of a Heavy Majorana Neutrino at the LHC

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Abstract

We consider a new interaction between a heavy Majorana neutrino (N) and a charged Higgs boson (H^\pm), and show that it can have drastic implications on lepton number violating (LNV) signal of same-sign dileptons at the LHC. The LNV signal of heavy Majorana neutrinos previously considered at the LHC, $pp \rightarrow \ell^+ N \rightarrow \ell^+ \ell^+ W^-$, may be overwhelmed by $pp \rightarrow \ell^+ N \rightarrow \ell^+ \ell^+ H^-$. With the subsequent decays $H^- \rightarrow \bar{t}b$ or $H^- \rightarrow W^- H^0$, the heavy Majorana neutrino production leads to the spectacular events of $\ell^+ \ell^+ b\bar{b} + 2$ jets. We also explore the case $m_N < m_{H^\pm}$, where the decay $H^+ \rightarrow \ell^+ N$ can become the dominant N -production mechanism at the LHC. In particular, we show that the process $gb \rightarrow tH^-$ followed by $t \rightarrow bW^+$ and $H^- \rightarrow \ell^- N \rightarrow \ell^- \ell^- W^+$ could lead to another type of spectacular events of $\ell^- \ell^- b + 4$ jets.

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I. INTRODUCTION

The discovery of neutrino oscillations stands as the first direct evidence for physics beyond the Standard Model (SM), indicating that neutrinos are massive and that their flavors mix. The minimal realization of beyond the SM physics that can account for the observed sub-eV neutrino masses and mixings is constructed simply by adding heavy right-handed neutrino fields, N , to the SM Lagrangian (we will denote this minimal setup by ν SM):

$$\mathcal{L}_{\nu SM} \equiv \mathcal{L}_{SM} + \frac{1}{2}MNN + (Y_H LHN + h.c.), \quad (1)$$

where M is the right-handed Majorana neutrino mass scale, L is an SU(2) leptonic doublet and H is the SM Higgs doublet. The ν SM Lagrangian gives rise to the light neutrinos mass matrix through the classic seesaw mechanism:

$$m_\nu = -m_D M^{-1} m_D^T, \quad (2)$$

where $m_D = vY_H$ and $v = \langle H \rangle \sim 175$ GeV. Thus, $m_\nu \sim \mathcal{O}(10^{-2}$ eV) implies that either $m_N \sim 10^{15}$ GeV, $Y_H \sim \mathcal{O}(1)$; or $m_N \sim m_W$ and $Y_H \sim 10^{-7}$. Evidently, if there are heavy Majorana neutrinos at the electroweak (EW) scale, then the seesaw mechanism would seem to be somewhat unnatural and physics beyond the classic seesaw would be needed in order to understand the very small Yukawa couplings associated with the neutrino mass generation.

In this minimal ν SM framework, N can interact with the SM gauge bosons and Higgs through its mixing with the light SM SU(2) ν_L fields (see e.g., [1]):

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}U_{\ell N}\bar{\ell}\gamma^\mu P_L N W_\mu^- + h.c., \quad (3)$$

$$\mathcal{L}_Z = -\frac{g}{2c_W}U_{\ell N}\bar{\nu}_\ell\gamma^\mu P_L N Z_\mu + h.c., \quad (4)$$

$$\mathcal{L}_H = -\frac{g}{2}\frac{m_N}{m_W}U_{\ell N}\bar{\nu}_\ell P_R N H^0 + h.c., \quad (5)$$

where $P_{L,R} \equiv (1 \mp \gamma_5)/2$ and $U_{\ell N}$ are the $\nu_{\ell,L} - N$ mixing elements. However, with no additional assumptions or symmetries imposed on the ν SM Lagrangian in (1), these heavy-to-light mixing elements are restricted to be vanishingly small by the seesaw mechanism itself. In particular, the seesaw relation in (2) leads to $U_{\ell N} \sim \sqrt{m_\nu/m_N}$. Therefore, we have $U_{\ell N} \rightarrow 0$ in order to successfully generate m_ν in the sub-eV range, irrespective of whether $m_N \sim m_W$ or $m_N \sim 10^{15}$ GeV. It follows that, within the minimal seesaw setup embedded

in the ν SM, the heavy Majorana neutrinos completely decouple and no signals of N are expected in collider experiments.

On the other hand, as argued above, naturalness (i.e., requiring the neutrino Yukawa terms to be of order 1) implies that there is new physics beyond the minimal seesaw mechanism of the ν SM type if indeed $m_N \sim m_W$. In this case it is, therefore, phenomenologically viable to expect that the interactions of N with the EW degrees of freedom are not necessarily suppressed, leading to very interesting lepton-number-violating (LNV) phenomenology mediated by N at high-energy colliders such as the Tevatron, the CERN Large Hadron Collider (LHC) and the International Linear Collider (ILC).

Indeed, collider phenomenology of heavy Majorana neutrinos has regained interest in the past decade due to their potential role in generating the observed sub-eV light neutrino masses. With the upcoming LHC and the future ILC e^+e^- collider, the search for LNV signals mediated by heavy Majorana neutrinos is particularly well motivated. This had led to some extensive studies of heavy Majorana neutrinos in pp and $p\bar{p}$ collisions [2, 3, 4, 5, 6], at an e^+e^- [4, 7], e^-e^- [8, 9] and $e^-\gamma$ collisions [4, 10] and at an ep machine [4, 7, 11]. In addition, LNV decays mediated by exchanges of heavy Majorana neutrinos were studied in top-quark and W -boson decays [12] and in rare charged meson and lepton decays [13].

It should be clear that, although not always explicitly stated, the assumption which underlies *all* the above studies is that at least one heavy Majorana neutrino has an unsuppressed coupling/mixing with the SM gauge bosons and Higgs and that N production (and decays) at high-energy colliders is induced by this coupling. That is, that $U_{\ell N} \sim \mathcal{O}(1)$ – many orders of magnitudes larger than its naively expected size within the classic seesaw, which necessarily implies new physics beyond the minimal ν SM.

In general such new physics can be parametrized by corrections to the ν SM Lagrangian represented as a series of effective operators \mathcal{O}_i which are constructed using the ν SM fields and whose coefficients are suppressed by powers of $1/\Lambda$, where Λ is the scale of the new physics:

$$\mathcal{L} = \mathcal{L}_{\nu SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \alpha_i \mathcal{O}_i^n . \quad (6)$$

For example, the dimension 6 operator [14]:

$$\mathcal{O}_{Ne\phi} = i \left(\bar{N} \gamma^\mu \ell_R \right) \left(\phi^T \epsilon D_\mu \phi \right) , \quad (7)$$

can generate the new V+A charged interaction:

$$\mathcal{L}_W = \alpha_{\ell N} \bar{N} \gamma^\mu P_R \ell W_\mu^+ + h.c. , \quad (8)$$

with $\alpha_{\ell N} \sim \mathcal{O}(v^2/\Lambda^2)$ (i.e., when the coefficient in front of $\mathcal{O}_{Ne\phi}$ is naturally $\alpha_{Ne\phi} \sim \mathcal{O}(1)$) [14]. Thus, if the new physics is around the TeV scale we can expect $\alpha_{\ell N} \lesssim 0.1$. However, even with this generic parametrization of new physics it is hard to see how the unsuppressed SM-like $N \gamma^\mu P_L \ell W_\mu^+$ interaction in (3) can be generated, when the new heavy Majorana fields are right-handed. To generate such a large SM-like coupling one has to assume that other non-seesaw or seesaw-like mechanisms exist which utilize some fine-tuned relations or extra symmetries in the neutrino sector [15, 16, 17, 18, 19]

Here we will take a phenomenological approach towards the V-A coupling of $\ell N W^+$, governed by the mixing parameter $U_{\ell N}$, assumed to be of $\mathcal{O}(1)$ a priori. EW precision data from LEP imply that $U_{\ell N} \lesssim 0.1$ if $m_N > m_Z$ [20, 21] and $U_{\ell N} \lesssim 0.01$ if $m_N < m_Z$ [21]. Indeed, the leading N signature at the LHC is traditionally assumed to be driven by the unsuppressed $N \ell^+ W^-$ interaction vertex as in Eq. (3) [3, 4, 5, 6] $pp \rightarrow W^{+\star} \rightarrow \mu^+ N \rightarrow \mu^+ \mu^+ W^- \rightarrow \mu^+ \mu^+ jj$, where j stands for a light-quark jet. In recent analyses [3, 6], it was found that this process may be observed at the LHC at the 5σ level, with an integrated luminosity of 30–100 fb $^{-1}$, if $U_{\ell N} \lesssim 0.1$ and $m_N \lesssim 200 - 250$ GeV. The signal and background estimates in these studies only apply to the specific final state $\mu^+ \mu^+ jj$ with no missing energy. In general, however, the N -production and decay patterns may be drastically altered due to additional operators involving the interactions of N with the other low-energy degrees of freedom of the underlying new physics. This can lead to interesting new LNV signatures which may be easier to trace. For example, the above Drell-Yan like process, $pp \rightarrow \mu^+ N$, may not be the dominant N -production mechanism at the LHC, in which case new strategies for N -discovery should be adopted.

In this paper we wish to explore one specific example of beyond the ν SM physics, in which N -production and decays may be completely altered. Since non-zero neutrino mass necessarily requires new physics beyond the SM and since the extension for the SM Higgs sector is well motivated in many theories beyond the SM, it is natural to consider the interplay of both. In particular, we will focus on a heavy Majorana neutrino potentially accessible at the LHC with a mass in the range $10 \text{ GeV} \lesssim m_N \lesssim 500 \text{ GeV}$, and the observation feasibility through its interactions with a generic new charge Higgs boson.

The paper is organized as follows: in section II we lay out the theoretical setup. In sections III - V we discuss N -phenomenology at the LHC in the presence of the new $N - H^+$ interaction in the two cases $m_N > m_{H^+}$ and $m_N < m_{H^+}$, and in section VI we summarize and give our concluding remarks.

II. THE CHARGED HIGGS BOSON AND A HEAVY MAJORANA NEUTRINO

We first introduce a generic new ℓNH^+ interaction in a relative model-independent approach

$$\mathcal{L}_{\ell NH^+} = \frac{g}{\sqrt{2}} \xi_{\ell N} \frac{m_N}{m_W} \bar{N} P_L \ell H^+ + h.c. , \quad (9)$$

where $\xi_{\ell N}$ are dimensionless parameters whose size depend on the underlying new physics.

In particular, since $\mathcal{L}_{\ell NH^+}$ is a typical dimension 4 Yukawa-like term, one naturally expects $\xi \sim \mathcal{O}(1)$ if the new physics contains EW-scale new scalar fields as well as heavy Majorana neutrinos. Alternatively, such an effective interaction can be generated in the underlying theory by exchanges of heavy gauge-bosons or heavy fermions. In this case, guided by the effective Lagrangian prescription in (6) and by naturalness (i.e., $\alpha_i \sim \mathcal{O}(1)$), when these heavy particles are integrated out we expect:

$$\xi \sim \frac{\sqrt{2} m_W}{g} \frac{v^2}{m_N \Lambda^2}, \quad (10)$$

where Λ is roughly the mass of the new heavy particle that gives rise to the ℓNH^+ interaction in (9). Thus, when $m_N \sim m_W$ we can expect e.g., $\xi \gtrsim 0.1$ if $\Lambda \sim 1$ TeV.

Since there is no direct experimental constraint on ξ that we know of, we will take a phenomenological approach towards the new $\xi_{\ell N}$, exploring the implications of $\mathcal{L}_{\ell NH^+}$ for ξ in the range $0 < \xi < 1$ (note that $\xi \sim \mathcal{O}(1)$ is also consistent with perturbative unitarity if $m_N \lesssim 700$ GeV, as was noted in [9]). Then, depending on its exact size, these new ℓNH^+ interactions can have surprising implications on N -phenomenology at high-energy colliders. For instance, in [9] it was shown that such a coupling can drive a LNV same-sign charged Higgs pair-production signal, $e^- e^- \rightarrow H^- H^-$, at an observable rate at an ILC even if $m_N \sim 1000$ TeV.

As for collider phenomenology of N in the presence of the interactions (3)-(5), (8) and (9), we adopt a “one-coupling scheme” for simplicity, assuming that only one of the mixing

angles dominates, e.g., $U_{\mu N} \gg U_{eN}, U_{\tau N}$ and similarly, $\xi_{\mu N} \gg \xi_{eN}, \xi_{\tau N}$. These elements will be denoted hereafter by $U \equiv U_{\mu N}$ and $\xi \equiv \xi_{\mu N}$.

A. N decay in the presence of H^\pm

In the framework where a new μNH^+ interaction is present, N will predominantly decay via the kinematically accessible channels

$$N \rightarrow W^\mp \mu^\pm, Z \nu_\mu, H^0 \nu_\mu, H^\mp \mu^\pm. \quad (11)$$

The partial widths for these decay channels are given by

$$\begin{aligned} \Gamma(N \rightarrow \mu^\pm W^\mp) &\approx \frac{U^2 m_N^3}{16\pi v^2} (1 + 2r_W)(1 - r_W)^2, \\ \Gamma(N \rightarrow \nu_\mu Z) &\approx \frac{U^2 m_N^3}{16\pi v^2} (1 + 2r_Z)(1 - r_Z)^2, \\ \Gamma(N \rightarrow \nu_\mu H^0) &\approx \frac{U^2 m_N^3}{16\pi v^2} (1 - r_{H^0})^2, \\ \Gamma(N \rightarrow \mu^\pm H^\mp) &\approx \frac{\xi^2 m_N^3}{16\pi v^2} (1 - r_{H^\pm})^2, \end{aligned} \quad (12)$$

where $r_i = m_i^2/m_N^2$. A useful limit for illustrating that is $m_N^2 \gg m_W^2, m_Z^2, m_{H^0}^2, m_{H^\pm}^2$, in which case the total decay width of N can be conveniently written as:

$$\Gamma_N \approx \Gamma_N^0 \cdot (4U^2 + 2\xi^2), \quad \Gamma_N^0 \equiv \frac{g^2}{64\pi} \frac{m_N^2}{m_W^2} m_N = \frac{m_N^3}{16\pi v^2}. \quad (13)$$

Clearly then, N can become “W/Z/ H^0 -phobic” if $\xi^2 \gg U^2$, since in this case its width is dominated by its decays to the new charged Higgs. To demonstrate the effect of the μNH^+ coupling ξ on the pattern of the N -decays, we plot in Fig. 1(a) the BR’s for the decays $N \rightarrow \mu^+ W^-$ and $N \rightarrow \mu^+ H^-$ as a function of ξ , for $m_N = 150$ GeV and $m_{H^\pm} = 100$ GeV, and setting $U = 0.1$ and $m_{H^0} = 200$ GeV. We can indeed see the sharp drop of the $BR(N \rightarrow \mu^+ W^-)$ as ξ increases. In particular, for $\xi \sim \mathcal{O}(1)$, we obtain $BR(N \rightarrow \mu^+ W^-) \sim 0.01$ while $BR(N \rightarrow \mu^+ H^-, \mu^- H^+)$ saturate the decay.

In Figs. 1(b) we further plot the decays $N \rightarrow \mu^+ W^-$ and $N \rightarrow \mu^+ H^-$ as a function of m_N , for $\xi = 1$ and for $m_{H^\pm} = 150$ GeV, $m_{H^0} = 200$ GeV and setting U to its largest allowed values depending on m_N , i.e., $U = 0.1$ for $m_N > m_Z$ and $U = 0.01$ for $m_N < m_Z$. Below the threshold $m_N < m_{H^\pm}, m_W$, the off-shell effects have been taken into account. Way above the threshold, the relative branchings for $N \rightarrow \mu^+ H^-$ and $N \rightarrow \mu^+ W^-$ is governed by ξ^2/U^2 .

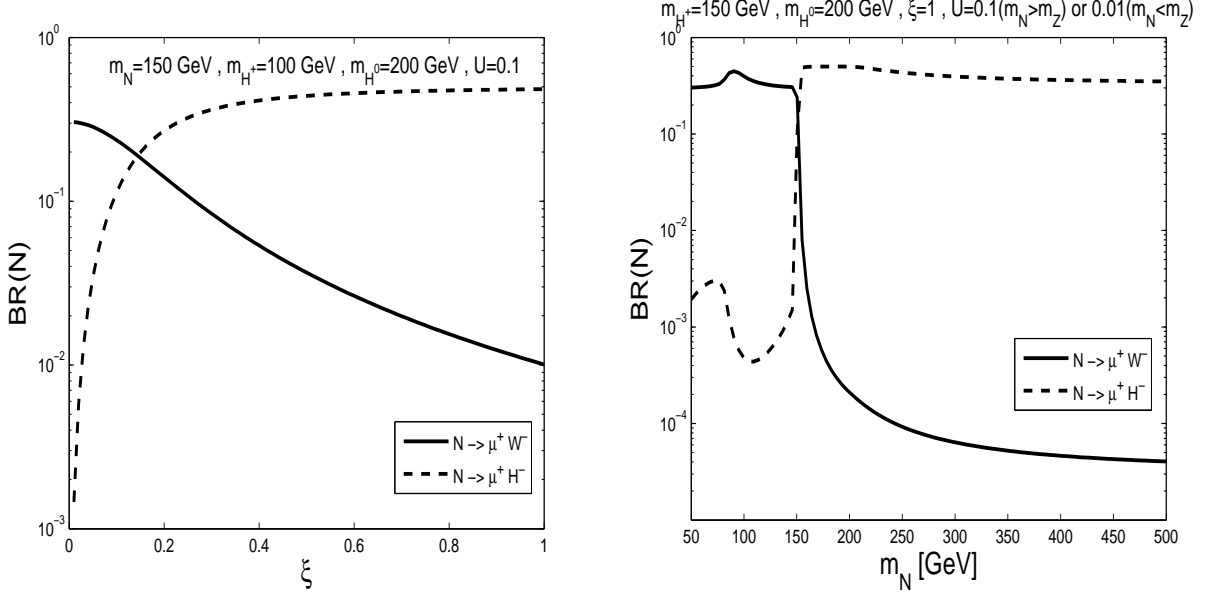


FIG. 1: (a). The branching fractions for the decays $N \rightarrow \mu^+ W^-$ (solid line) and $N \rightarrow \mu^+ H^-$ (dashed line) as a function of ξ , for $m_N = 150$ GeV, $m_{H^+} = 100$ GeV, $m_{H^0} = 200$ GeV and $U = 0.1$. (b). The branching fractions for the decays $N \rightarrow \mu^+ W^-$ (solid line) and $N \rightarrow \mu^+ H^-$ (dashed line) as a function of m_N , for $m_{H^+} = 150$ GeV, $m_{H^0} = 200$ GeV, $\xi = 1$, with $U = 0.1$ for $m_N > m_Z$ and $U = 0.01$ for $m_N < m_Z$. When $m_N < m_{H^+}$ or $m_N < m_W$ the curves correspond to decays to off-shell H^+ or W^+ , respectively.

B. Including H^\pm decays

As a concrete example for illustration, let us assume that the H^\pm -SM couplings have similar structure as the charged Higgs couplings in generic multi Higgs doublet models:

$$\mathcal{L}_{H^+ud} = \frac{g}{\sqrt{2}} \bar{u} \left(f_v^u \frac{m_u}{m_W} P_L + f_v^d \frac{m_d}{m_W} P_R \right) d H^+ + h.c. , \quad (14)$$

$$\mathcal{L}_{H^+\nu_\ell\ell} = \frac{g}{\sqrt{2}} f_v^\ell \frac{m_\ell}{m_W} \bar{\nu}_\ell P_R \ell H^+ + h.c. , \quad (15)$$

$$\mathcal{L}_{H^+H^0W^-} = \frac{ig}{2} f_W W^+ \cdot (H^0 \partial H^- - \partial H^0 H^-) + h.c. , \quad (16)$$

and that the dominant H^+ decays channels are

$$H^+ \rightarrow \tau^+ \nu, \ c \bar{s}, \ t \bar{b}, \ \mu^+ N, \ W^+ H^0, \quad (17)$$

when kinematically allowed. As an example, in Fig. 2(a) we show the expected BR's for the decays $N \rightarrow \mu^+ W^-$ and $N \rightarrow \mu^+ t \bar{b}$ as a function of the $\mu N H^+$ coupling strength ξ , setting

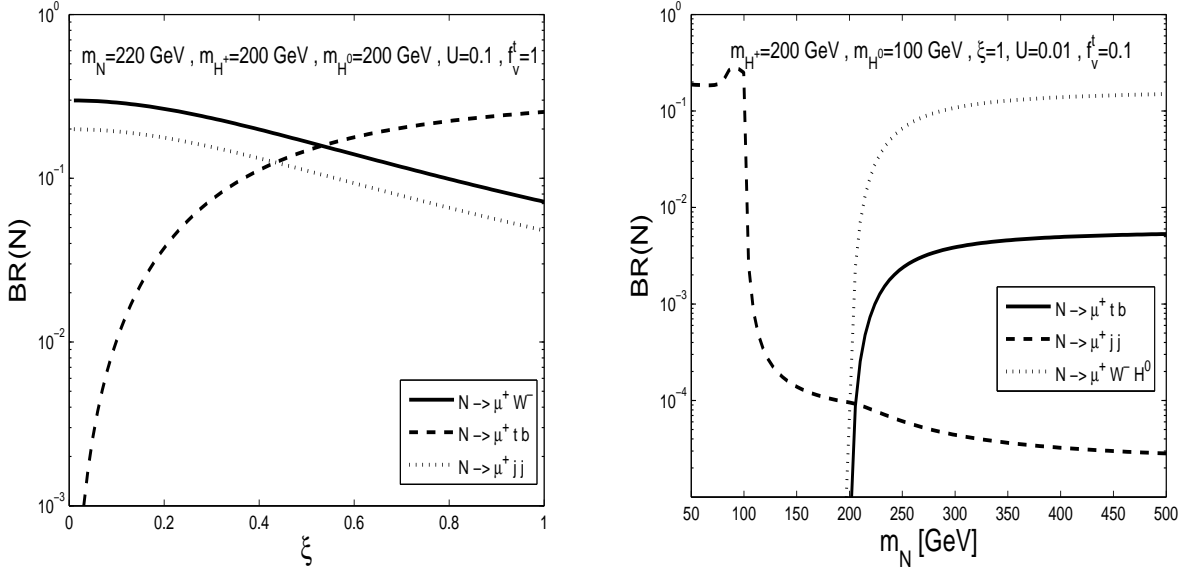


FIG. 2: (a). The branching fractions for the decays $N \rightarrow \mu^+ W^-$ (solid line), $N \rightarrow \mu^+ \bar{t} b$ (dashed line) and $N \rightarrow \mu^+ jj$ from W decay (dotted line) as a function of ξ , for $m_N = 220$ GeV, $m_{H^+} = 200$ GeV, $m_{H^0} = 200$ GeV, $U = 0.1$ and $f_v^t = 1$ (see text). (b). The branching fractions for the decays $N \rightarrow \mu^+ \bar{t} b$ (solid line), $N \rightarrow \mu^+ jj$ (dashed line) and $N \rightarrow \mu^+ W^- H^0$ (dotted line) as a function of m_N , for $m_{H^+} = 200$ GeV, $m_{H^0} = 100$ GeV, $\xi = 1$, $U = 0.01$ and $f_v^t = 0.1$.

$U = 0.1$, $m_N = 220$ GeV and $m_{H^+} = m_{H^0} = 200$ GeV. For the H^+ couplings we took $f_v^c = f_v^t = f_v^\tau = f_W = 1$ and $f_v^d = 0$. The channel $N \rightarrow \mu^+ jj$ from $W \rightarrow jj$ is also plotted for comparison by the dotted curve. We see that for this set of masses and couplings, the channel $N \rightarrow \mu^+ \bar{t} b$ dominates over the previously studied $N \rightarrow \mu^+ jj$ one when $\xi \gtrsim 0.5$.

To further explore the potential deviations from “standard” N -phenomenology at future colliders, we plot in Fig. 2(b) the BR’s for the decays $N \rightarrow \mu^+ \bar{t} b$, $N \rightarrow \mu^+ jj$ and $N \rightarrow \mu^+ W^- H^0$ for another set of inputs and find that the WH^0 mode can be dominant, when $m_{H^+} > m_{H^0}$ and if the $H^+ tb$ coupling is suppressed.

In the next section we will show that these new decay channels of N via an intermediate H^+ , can have interesting implication for N -phenomenology at the LHC.

III. SAME-SIGN DI-MUONS SIGNALS: $pp \rightarrow \mu^+ \mu^+ W^-$ VERSUS $pp \rightarrow \mu^+ \mu^+ H^-$

As reiterated recently, a heavy Majorana neutrino may be searched for at the LHC via the Drell-Yan production in [2, 3, 4, 5, 6]

$$pp \rightarrow \mu^+ N + h.c. , \quad (18)$$

with $N \rightarrow \mu^\pm W^\mp$, leading to the spectacular signal of $\mu^\pm \mu^\pm + 2$ jets. As discussed above, the existence of the $\ell N H^+$ interaction in (9) may change the N decay pattern significantly, possibly resulting in $N \rightarrow \mu^\pm H^\mp$ as the dominant mode. We will study this effect in more detail below.

Denoting the cross-section $\sigma_N \equiv \sigma(pp \rightarrow \mu^+ N)$, we can generically study the unknown couplings as parameterized in Eqs. (3) and (8), and expect $\sigma_N = U^2 \sigma_{V-A}$ or $\sigma_N = \alpha_{\mu N}^2 \sigma_{V+A}$ if $U \ll \alpha_{\mu N}$, where U and $\alpha_{\mu N}$ are generic (V-A) and (V+A) $\mu N W$ couplings, respectively. Since $\sigma_{V-A} = \sigma_{V+A}$ (up to factors that linearly depend on the cosine of the center of mass scattering angle, $\cos \theta$, which vanish after symmetrically integrating over phase-space), we will generically denote $\sigma_N \propto U^2$ regardless of whether it is generated by the $V - A$ or the $V + A$ coupling. In particular, for $U \sim 0.1$ (i.e., at its upper limit value), one gets $\sigma_N \sim 100$ fb or $\sigma_N \sim 10$ fb for $m_N \sim 100$ or 200 GeV, respectively, with no cuts [3, 4, 5, 6]. The kinematical cuts applied to the final state particles after the N decays, e.g., to $\mu^+ \mu^+ jj$ when $N \rightarrow \mu^+ W^- \rightarrow \mu^+ jj$, are expected to reduce these cross-sections by less than an order of magnitude [3, 6].

For m_N in the range of several hundreds GeV, the total N width is at most a few percents of m_N . Thus, we can take the narrow width approximation (NWA):

$$\begin{aligned} \sigma(pp \rightarrow \mu^+ \mu^+ W^\mp) &\sim \sigma(pp \rightarrow \mu^+ N) \times BR(N \rightarrow \mu^+ W^\mp) , \\ \sigma(pp \rightarrow \mu^+ \mu^+ H^\mp) &\sim \sigma(pp \rightarrow \mu^+ N) \times BR(N \rightarrow \mu^+ H^\mp) , \end{aligned} \quad (19)$$

as a good estimate of the total same-sign di-muon cross-sections above. Using the NWA, in Table I we give some sample results which compare between the above two signals, for the case $m_N > m_{H^+} > m_W$ and when $\xi = 1$, $U = 0.1$, without applying any kinematical cuts. To give a complete picture for the expected same-sign di-muons signal at the LHC, we list in Table I the total cross-sections summing the contributions from both the $\mu^+ \mu^+$ and the $\mu^- \mu^-$ channels. We denote these total cross-sections by $\sigma(pp \rightarrow \mu\mu W) \equiv \sigma(pp \rightarrow$

m_N [GeV]	m_{H^+} [GeV]	$pp \rightarrow \mu^+ N$ σ [fb]	$pp \rightarrow \mu^- N$ σ [fb]	$N \rightarrow \mu^\pm W^\mp$ BR	$N \rightarrow \mu^\pm H^\mp$ BR	$pp \rightarrow \mu\mu W$ σ [fb]	$pp \rightarrow \mu\mu H$ σ [fb]
100	80	155.6	106.9	0.008	0.49	2.1	128.6
150	120	29.4	18.9	0.022	0.46	1.1	22.2
200	150	10.4	6.3	0.02	0.47	0.33	7.9
220	200	7.4	4.4	0.07	0.25	0.83	2.95

TABLE I: Branching fractions (BR) for the two-body decays $N \rightarrow \mu^\pm W^\mp$, $\mu^\pm H^\mp$ and cross-sections in fb for the Drell-Yan N -production $pp \rightarrow \mu^\pm N$ and for the total same-sign dimuon signals at the LHC: $\sigma(pp \rightarrow \mu\mu W) \equiv \sigma(pp \rightarrow \mu^+\mu^+W^-) + \sigma(pp \rightarrow \mu^-\mu^-W^+)$ and similarly for $\sigma(pp \rightarrow \mu\mu H)$, see also text. The cross-sections are evaluated using the CTEQ6M parton distribution functions and results are given for various sets of N and H^+ masses, for $\xi = 1$, $U = 0.1$ and for $m_{H^0} = 200$ GeV. No cuts are applied.

$\mu^+\mu^+W^-) + \sigma(pp \rightarrow \mu^-\mu^-W^+)$ and similarly for $\sigma(pp \rightarrow \mu\mu H)$, reminding the reader that at the LHC the positively charged di-muons rate is about 1.5 times larger than the negatively charged dimuons one. As seen from Table I, the cross-section for $\mu^+\mu^+H^-$ can become more than an order of magnitude larger than that of $\mu^+\mu^+W^-$ (similar for the $\mu^-\mu^-$ channels), if $m_N > m_{H^+}$ and $\xi \sim 1$, even if one assumes the largest possible cross-section for $\mu^+\mu^+W^-$, i.e., taking $U = 0.1$. In such a case, heavy Majorana neutrinos should be searched for at the LHC through their decay to a charged Higgs boson. The representative cross section can be the order of $1 - 100$ fb, leading to $10^2 - 10^4$ events with an integrated luminosity of 100 fb^{-1} before acceptance cuts on the final states.

Of particular interest is the situation of H^\pm decay above the thresholds. For $m_{H^+} > m_t + m_b$, the single-top production in association with a pair of same-sign di-muons will

become the dominant channel

$$pp \rightarrow \mu^+ N \rightarrow \mu^+ \mu^+ H^- \rightarrow \mu^+ \mu^+ \bar{t} b, \quad (20)$$

with a BR to be about 25% (see Fig. 2(a)) – almost an order of magnitude larger than that of $pp \rightarrow \mu^+ N \rightarrow \mu^+ \mu^+ jj$. After the top decays, this single-top LNV channel is manifest through $\mu^+ \mu^+ \bar{t} b \rightarrow \mu^+ \mu^+ b b j j$, i.e., a pair of same-sign di-muons in association with a pair of light jets and a pair of b -jets, where the two light jets reconstruct m_W , which combine with one b -jet to reconstruct the top mass. Along with the second b -jet, the whole $b \bar{b} j j$ system further reconstructs the charged Higgs mass. For $m_{H^+} > m_W + m_{H^0}$, the new channel

$$pp \rightarrow \mu^+ N \rightarrow \mu^+ \mu^+ H^- \rightarrow \mu^+ \mu^+ W^- H^0, \quad (21)$$

can become even more important, having a BR at the level of 10% and dominating over the $pp \rightarrow \mu^+ N \rightarrow \mu^+ \mu^+ \bar{t} b$ and $pp \rightarrow \mu^+ N \rightarrow \mu^+ \mu^+ jj$ ones, if for example: $m_{H^+} = 200$ GeV, $m_{H^0} = 100$ GeV, $U = 0.01$, $\xi = 1$ and the H^+ couplings: $f_v^c = f_v^t = f_v^\tau = 0.1$, $f_v^d = 0$ and $f_W = 1$ (see Fig. 2(b)).¹ Similar to the single-top LNV signal of Eq. (20), the LNV $\mu^+ \mu^+ W^- H^0$ channel can also induce the signature $\mu^+ \mu^+ W^- H^0 \rightarrow \mu^+ \mu^+ b b j j$, but with different kinematics of the final state, namely the pair of b -jets reconstruct m_{H^0} .

As for the signal identification, we note that there are no SM processes with $\Delta L = 2$. All backgrounds are due to some misidentification of certain sources. Recent studies demonstrated that with judicious acceptance cuts, the SM backgrounds to the $\mu^+ \mu^+ jj$ signal can be effectively suppressed [3, 6]. With the presence of two more b -jets coming from a top-quark decay or from a Higgs decay, along with a pair of same-sign di-muons in the final state, we expect to significantly improve the signal to background ratio, in comparison with the $\mu^+ \mu^+ jj$ one. We do not plan to further quantify the signal identification in this work.

IV. NEW CONTRIBUTION WHEN $m_N < m_{H^+}$

Although the spectacular decay of $N \rightarrow H^\pm \ell^\mp$ is kinematically not allowed for this case, the inverted process $H^+ \rightarrow \ell^+ N$ can become the leading N -production mechanism. In this

¹ Note that $f_W = 1$ correspond, for example, to the coupling in a two Higgs doublets model (e.g., in the MSSM) when $\alpha = \beta$, where α and β are the neutral Higgs mixing angles in the CP-even and CP-odd sectors, respectively.

case the leading H^+ production mechanism will be $g\bar{b} \rightarrow \bar{t}H^+$ (and similarly $gb \rightarrow tH^-$), with a cross-section at the LHC ranging from $\mathcal{O}(1000 \text{ fb})$ if $m_{H^+} \sim 200 \text{ GeV}$ to $\mathcal{O}(100 \text{ fb})$ if $m_{H^+} \sim 600 \text{ GeV}$ [24]. This channel has been considered as a promising channel for the discovery of a charged Higgs boson [25]. Therefore, after H^+ decays via $H^+ \rightarrow \ell^+ N$, we expect the tN -associated production rate at the LHC to be:

$$\sigma_N(g\bar{b} \rightarrow \bar{t}H^+ \rightarrow \bar{t}\mu^+ N) \sim (100 - 1000 \text{ fb}) \times \text{BR}(H^+ \rightarrow \mu^+ N) , \quad (22)$$

for m_{H^+} of several hundreds GeV. Then, if $\xi \sim f_v^t \sim 1$, we expect $\text{BR}(H^+ \rightarrow \mu^+ N) \sim \text{BR}(H^+ \rightarrow t\bar{b}) \sim \mathcal{O}(1)$, in which case the N -signal top associated production channel in (22) can have a cross-section at the order of 100 fb, even if $m_N \sim 500 \text{ GeV}$. This is to be compared with the Drell-Yan $pp \rightarrow \mu^+ N$ production rate which is $\sigma(pp \rightarrow W^{+\ast} \rightarrow \mu^+ N) \sim 0.1 \text{ fb}$ for $m_N \sim 500 \text{ GeV}$. Thus, while no signal of heavy Majorana neutrinos with a mass around 500 GeV is expected at the LHC through the traditionally assumed Drell-Yan production mechanism, its production rate through H^+ decays can be as much as 3 orders of magnitude larger than the Drell-Yan one, possibly leading to hundreds-thousands of heavy Majorana neutrinos in association with a pair of $t\mu^+$ at the LHC.

When the N further decays there are several interesting signatures that arise from the above $\bar{t}\mu^+ N$ (or $t\mu^- N$) final state, depending on its couplings to the SM particles. Perhaps the simplest example is $pp \rightarrow \mu^+ \bar{t} N$ followed by $N \rightarrow \mu^+ W^-$, which will lead to the new LNV signature

$$\mu^+ \mu^+ \bar{t} W^- \rightarrow \mu^+ \mu^+ W^- W^- b, \quad (23)$$

i.e., same sign di-muons accompanied by an opposite sign W -pair and a hard b -jet, which reconstructs the top-quark and the H^+ . The hadronic decays of the $W^- W^-$ may be desirable for the confirmation of the lepton-number violation as well as for the m_t and m_{H^+} reconstruction. A comprehensive analysis of such new N -mediated LNV signal as well as the SM backgrounds is beyond the scope of this work, although once again we do not expect it too difficult for a signal identification. Clearly, though, such new LNV signals deserve to be separately addressed, since their kinematics and background completely depart from the ones expected for the widely studied $\mu^+ \mu^+ jj$ one, and, in particular, since hundreds to thousands of such events are expected at the LHC if $\xi \sim 1$.

Finally, to conclude this section we note that if $m_N < m_W < m_{H^+}$, then one might expect an enhancement in the Drell-Yan process $pp \rightarrow W^+ \rightarrow \mu^+ N$ since the s-channel W^+ can

resonate, giving rise to a peak in the invariant μ^+N mass, which might be easier to handle due to its simplicity. However, since the limits on the $\mu W N$ coupling are more stringent in this N -mass range, i.e., $U \lesssim 0.01$ for $m_N \lesssim m_W$ [21], one expects at most (when $U \sim 0.01$) $\sigma(pp \rightarrow W^+ \rightarrow \mu^+ N) \sim 0.1 - 10$ [fb] for $m_N \sim 40 - 80$ GeV, respectively, after applying typical LHC cuts, see e.g., [6]. Evidently, even in the case $m_N < m_W < m_{H^+}$ we expect $H^+ \rightarrow \mu^+ N$ to be the dominant N -production mechanism at the LHC.

V. SUMMARY AND DISCUSSION

We have argued that naturalness of the seesaw mechanism, in the sense of having $\mathcal{O}(1)$ neutrino Yukawa terms, requires that either $m_N \sim 10^{16}$ GeV or that new physics beyond the classic seesaw mechanism exist in the neutrino sector if m_N is close to the EW-scale. Therefore, in the latter case when e.g., $m_N \sim 100 - 1000$ GeV, we expect that the new physics will generate $\mathcal{O}(1)$ couplings between the heavy Majorana neutrinos and the SM particles as well as between the heavy Majorana neutrinos and the other EW-scale degrees of freedom of the underlying new physics. These new couplings can then be manifest through new LNV signals, mediated by the heavy Majorana neutrinos, at future high-energy colliders such as the LHC and the ILC.

In this note we have considered one fairly model-independent example of such TeV scale new physics that can drastically change what is considered to be the conventional N -phenomenology at the LHC. In particular, we have assumed that there is an $\mathcal{O}(1)$ coupling between the heavy Majorana neutrino and a new charged Higgs of the underlying theory. We then showed that such a new interaction term can have interesting new implications on LNV same-sign lepton pair signals at the LHC.

For example, we found that the frequently-studied leading LNV signal of heavy Majorana neutrinos at the LHC, $pp \rightarrow W^+ \rightarrow \ell^+ N \rightarrow \ell^+ \ell^+ W^-$, can become irrelevant in the presence of a sizable $\ell N H^+$ coupling, since if $\text{BR}(N \rightarrow \ell^+ H^-) \gg \text{BR}(N \rightarrow \ell^+ W^-)$, the LNV signal of a pair of same-sign charged leptons in association with a charged Higgs, $pp \rightarrow \ell^+ N \rightarrow \ell^+ \ell^+ H^-$ become dominant and can lead to new LNV signatures such as $pp \rightarrow \ell^+ N \rightarrow \ell^+ \ell^+ \bar{t} b$ and $pp \rightarrow \ell^+ N \rightarrow \ell^+ \ell^+ W^- H^0$.

We have also shown that, in the case $m_N < m_{H^+}$, the decay $H^+ \rightarrow \ell^+ N$ is expected to become the dominant N -production mechanism at the LHC, possibly leading to hundreds-

thousands LNV events mediated by the heavy Majorana neutrinos, e.g., such as a new N -single top associated production $pp \rightarrow \ell^- \ell^- t W^+ \rightarrow \ell^- \ell^- W^+ W^+ b$.

We did not perform any signal to background analysis, as our goal was only to emphasize that new physics associated with heavy Majorana neutrinos can be manifest in various, sometimes unexpected, signals and, as such, may call for new strategies in the search for lepton number violation at future colliders. However, due to the additional b -quarks and light jets on top of the spectacular $\mu^\pm \mu^\pm jj$ signal, we expect that the SM backgrounds will be even easier to deal with than commonly studied $\mu\mu jj$ channel.

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